IAF-01-Q.2.08

Project Galileo
From Ganymede Back to Io

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52nd International Astronautical Congress
1-5 Oct 2001/Toulouse, France

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Abstract

Galileo has now completed two years of the Galileo Millennium Mission and the spacecraft continues to gather new and exciting observations of the Jupiter system. In late December, 2000, Galileo teamed with Cassini in the first ever collaboration between two missions to simultaneously study an outer planet and its surrounding environment. The unique opportunity of having two very capable spacecraft perform complementary observations is yielding new insights into the interactions of the solar wind with the magnetosphere, the atmospheric dynamics of Jupiter, the rings, and the tenuous atmospheres of Ganymede and Io. While Galileo provided high-resolution remote sensing observations during its Ganymede 29 encounter, Cassini acquired large-scale contextual views. Both spacecraft observed magnetospheric bow shock crossings and the same high velocity dust stream originating from the vicinity of Io. Following the successful Io encounters in late 1999, the Galileo mission was specifically designed to reduce radiation damage by keeping the spacecraft outside the intense radiation environment close to Jupiter with the goal of being operational when Cassini flew by en route to Saturn. Following Ganymede 29, the focus of the mission shifted back to Io as the spacecraft performed a gravity assist at Callisto to set up Io flyby geometries enabling definitive observations of that moon's magnetic field.

For a 14 week period around the Ganymede 29 perijove passage, Galileo collected continuous fields and particles data providing a complete slice from the solar wind through the magnetosphere and back out again. Collection of this data set required a new level of sequence design complexity to integrate real-time and recorded data acquisition with concurrent data playback Significant engineering issues and future plans are described. Each passage close to Jupiter brings new challenges to spacecraft operations as the cumulative radiation dosage approaches three and a-half times the design limits. Engineering data on spacecraft and instrument performance in this harsh environment is very useful to designers of future missions to Jupiter and its moons.

Science results which continue to change our fundamental understanding of the Jupiter system, particularly the jovian magnetosphere and magnetic fields of the satellites, are also presented.

1. Introduction

Galileo has now completed its second year of the Galileo Millennium Mission (GMM), the final mission extension after more than a decade of discovery. Figure 1 shows Galileo's journey from launch through interplanetary cruise to arrival at Jupiter and its subsequent

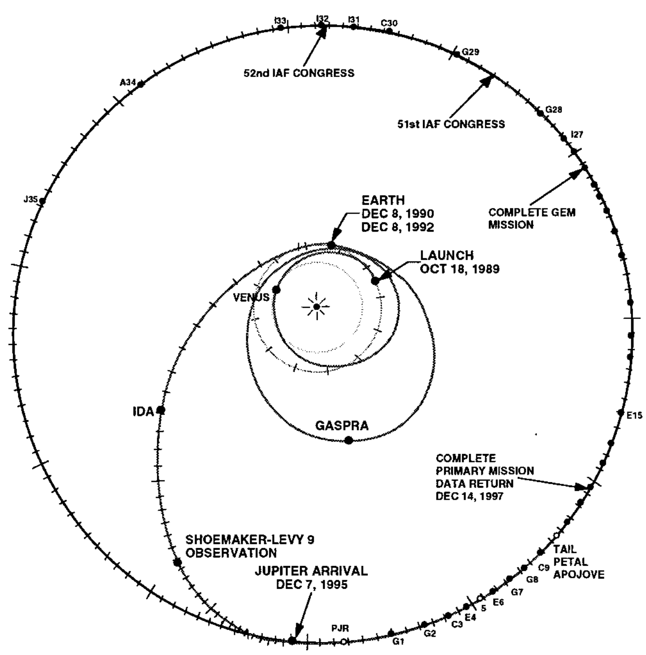

Figure 1. Heliocentric Progress

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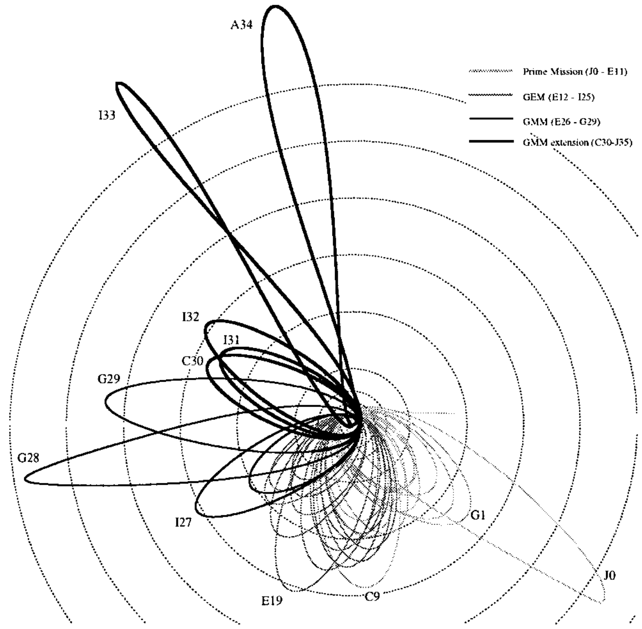

Figure 2. Detail Orbital Tour

heliocentric path as the spacecraft accompanies the giant planet along its orbit. Figure 2 shows the details of the orbital tour around Jupiter including the two-year prime mission[1-2], the two year Galileo Europa Mission (GEM) [3-4], and the GMM[5]. Each flyby targets the spacecraft for the next encounter.

In the past year, Galileo added three successful encounters to the continuing legacy of exploration of the Jupiter system: the planet, its moons, and its magnetosphere. Highlighting the year was the mutual success of the joint Galileo and Cassini flyby in December 2000. This unique collaboration between the two spacecraft provided spatial and temporal sampling of the Jupiter system which could only be accomplished cooperatively (Section 7). Galileo's continuous sampling of the magnetosphere for 14 weeks around the joint encounter provided a critical context for the study of the interaction between the solar wind and the Jovian magnetosphere.

The Galileo Project and NASA Headquarters agreed on an end of mission that balances outstanding science opportunities with the requirement to implement a planetary protection plan which prevents contamination of Europa. Following Ganymede 29, the joint encounter with Cassini, perijove was again lowered using a gravity assist at Callisto 30 to set up two polar flybys of Io to achieve high priority science missed at earlier Io encounters[5] (See Section 7.3). A third, and final, Io gravity assist places Galileo on a ballistic trajectory to impact Jupiter two orbits later. The intervening orbit, before impact, will take the spacecraft deep into the inner Jupiter system and within 1,000 km of Amalthea, one of the minor moons.

Radiation damage to spacecraft components remains a significant issue and the success of future encounters is not assured. Over the course of the next year, the radiation dose to which the spacecraft will be subjected increases to over four times the design limit. Effects are manifested in degraded performance of some of the engineering subsystems and science instruments as discussed in sections 3 and 5. Critical systems required for spacecraft control retain full functional redundancy.

2. GMM Extension

Having survived three Io encounters with a relatively healthy spacecraft, the project asked the flight team to once again step up to the challenge of planning a mission extension while continuing to perform ongoing mission operations. Groundwork for extending Galileo's mission was laid in a proposal submitted to a Comparative Planetary Review held by NASA Headquarters. Science teams under the leadership of the Science Planning and Operations Team (SPOT) used the baseline design to develop high-level science plans (an Orbit Activity Plan) consisting of integrated observation timelines and resource usage summaries for each orbit. For Callisto 30, Io 31, and Io 32, this work was accomplished from July 17 to October 20, 2000. Io 33 planning was delayed until January 15 to February 16, 2001, allowing the flight team to concentrate on generating and executing the command sequence for the Ganymede 29 encounter.

Generation of the actual command sequences for both the data gathering encounters and data playback cruise periods occur in the 8-weeks immediately preceding their execution onboard the spacecraft[5]. During long cruise periods leading up to and following Ganymede 29 encounter, a single command sequence could be generated at a time allowing the team time to develop the high level science plans for subsequent orbits and to collect science data during cruise. One of the challenges was to design commands to acquire continuous particles and fields data for a fourteen-week period centered on Ganymede 29 (See Section 6). With the orbital period decreasing to roughly two months starting with Callisto 30, both encounter and cruise command sequences have to be generated concurrently as was done during the prime mission and GEM[2].

3. Orbiter Performance Overview

3.1 Attitude and Articulation Control Subsystem (AACS)

The AACS subsystem has functioned well in the past year. The gyro electronics continue their pattern of degrading during encounter and annealing during the cruise portion of the orbit[4,5] (See Figure 3). Updated gyro scale factor parameters are uplinked to the spacecraft as needed after regularly scheduled gyro performance tests. Continuing a strategy adopted near the end of GEM, all encounters are flown in AACS cruise mode (star-based attitude reference) with gyros turned off while near Jupiter; one set of observations were successfully recorded in inertial mode (gyro-based attitude reference) in Ganymede 29 after the spacecraft was sufficiently outside of Jupiter's intense radiation belts. Star based attitude near Jupiter relies on a single bright star that is unlikely to be mis-identified due to background radiation noise.[6] Using a single star makes the attitude strategy vulnerable to periods when the star scanner bright body protection blocks out the area of sky around reference star. When this happens, AACS fault protection parameters are updated to allow the star to hibernate until the bright body risk is over. The star scanner optics have not shown any large increase in browning. Two different stars were used as the bright anchor stars during recent encounters; neither experienced any dropouts.

There have been two AACS related anomalies in the past year, neither of which is related to changes in the subsystem health. During Ganymede 28 cruise on June 19, 2000, Delta Velorum, one star being used for attitude reference, disappeared as seen by the star scanner for an 8-hour period. Analysis and independent verification revealed this to be a previously unknown variable star[7]

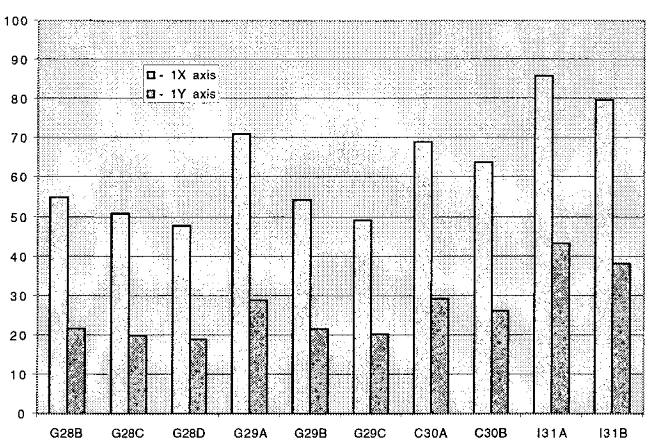

Figure 3. Gyro Degradation During GMM

(See Sections 4.3 and 8.1). During Ganymede 29 encounter, a sun avoidance fault protection algorithm tripped and sent the scan platform to a safe position. No observations were lost as a result; a slight mismatch in the calculated sun position onboard versus in ground-based modeling is the likely cause.

3.2 Command and Data Subsystem (CDS) and Data Memory Subsystem (DMS)

The command and data subsystem had another interesting year, with 3 patches sent to the flight software to correct for onboard problems. The first two patches completed the set of flight software changes needed to workaround a stuck bit in CDS memory[5] first identified at Io 24[5]. The first moved a data buffer used to process Near Infrared Mapping Spectrometer (NIMS) data off of the bad memory cell. The second patch fixed a problem that caused the I25A safing event[5], in which a relocated B side memory box was mistakenly recognized by flight software as being write-protected. The third patch was necessary for implementation of an onboard SSI instrument memory reload (See Section 5); this patch allowed certain areas of CDS memory to be written into by sequenced or real-time memory copy commands.

Transient bus resets continue to occur during each encounter, presumably induced by radiation exposure. Ganymede 29 experienced one bus reset while Callisto 30 and Io 31 both had two. More bus resets occur while outbound from Jupiter, rather than inbound. Because of a flight software patch implemented in 1999, the spacecraft correctly recognized all bus resets[4] and no sequences were interrupted.

3.3 Power/Pyrotechnic Subsystem (PPS)

The RTG (Radioisotope Thermoelectric Generator) output has continued to decay per predicts (about 7 Watts a year), dropping to 449 Watts in July 2001. The power management strategy is to cycle off one or both scan platform heaters to gain power when needed, generally during encounters while the scan platform and tape recorder are both in use. Using this strategy, power will not be a limiting factor in planning science operations for the remaining orbits.

3.4 Rocket-Propulsion Module (RPM)

The RPM subsystem has performed nominally in the past year. Standard activities included attitude turns, thruster maintenance, pointing and spin rate corrections, and orbit trim maneuvers (OTMs). From June 2000 through August 2001 the spacecraft performed 12 maneuvers (OTM-89 through OTM-100) to stay on the desired trajectory.

The propellant margin at the end of mission (post Amalthea 34) is currently predicted to be 1.8 kg. This includes recovering 10 kg of propellant originally bookkept at launch as part of the spacecraft dry mass and not available for use. Uncertainties in the orbit determination process led to several recent OTM's being larger than planned. There is a chance that a non-nominal flyby in I32 will require more propellant than remains onboard in order to continue the planned tour (See Section 9). In such a case, planetary protection requirements would lead the project to place Galileo on an impact trajectory earlier than planned, thus ending the mission early.

3.5 Temperature Control Subsystem

The +X thruster cluster, which has 2 heaters and 8 RHU's (radioisotope heater units), dropped in temperature due to degrading RHU's. While it continues to approach its lower allowable limit, the cluster is expected to remain above the limit through end-of-mission. The Bay A temperature, which affects the computer electronics' lifetime via temperature cycles, also continues to decrease due to RHU degradation. Several options are being studied to determine if a heater/component reconfiguration is necessary to maintain the Bay A temperature.

3.6 Telecommunications Subsystem

The communications subsystem connecting the spacecraft to the earth performed nominally this year in both uplink and downlink. The Ultra-Stable Oscillator (USO) frequency continues to drift, experiencing the largest jumps at perijove inside 8 R_J range when the highest radiation levels are encountered (See Figure 4). A 19-day period of solar conjunction, in which the sun interferes with the earth-spacecraft communications link, was passed successfully; there were only 14 days with no downlink received from the spacecraft.

4. Non-Instrument Anomalies

4.1 Playback SSI Data Type Anomaly

On September 12, 2000 during playback of Ganymede 28 data, a small amount of unexpected SSI data was played back in the wrong format, causing CDS error messages. No real time commands were necessary as playback continued uninterrupted. While the incident is not fully understood, a change in the generation of the playback commands precludes this from recurring.

4.2 Playback Search Anomaly

On January 6, 2001, while playing back SSI data, the DMS went to track 1 rather than the expected track 3. Upon investigation, it was found there was a 7% chance of this happening due to an autonomous "pause playback" triggered by PWS data processing occurring within a short time window of an autonomous track turnaround. Real time commands cleared the anomaly condition; no operating procedures were changed, as PWS data is not commonly selected during playback.

4.3 Variable Star Attitude Reference Anomaly

As mentioned in section 3.1, in June 2000 one star being used for attitude reference disappeared for an 8-hour period. See section 8.1 for details on how the variability of the star was discovered. An opportunity to verify the star's variability was identified on February 19, 2001 and the star (Delta Velorum) was added to the nominal star set beforehand so that the star scanner data could be used to watch the star "disappear." Unfortunately when Delta Velorum disappeared from the star scanner's view, another star was close enough in position and intensity to be mis-identified as Delta Velorum. This mis-identified star caused the celestial-based attitude knowledge to walk away from the actual spacecraft attitude. Two autonomous pointing corrects were performed based on this incorrect attitude reference, taking the spacecraft about 2 degrees away from the nominal attitude. At that point, attitude control algorithms could no longer lock-up on the star set and no further pointing corrections were issued. Real-time commands were sent to reload the correct star set and return to the nominal attitude via two more pointing corrects.

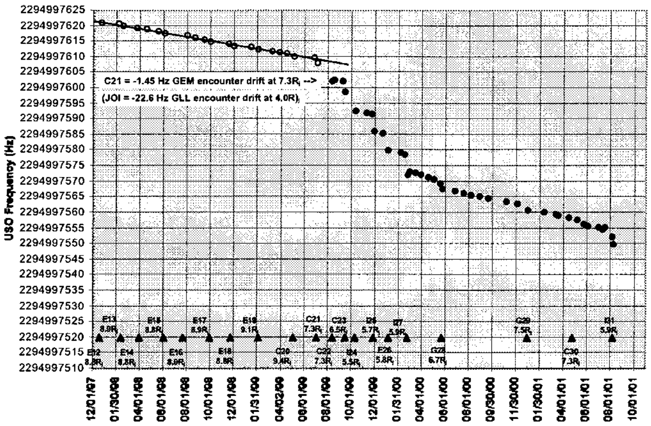

Figure 4. Galileo USO Frequency Drift

5. Instrument Status

5.1 SSI (Solid State Imager) Status

The SSI camera began to experience a problem in July 2000 during Ganymede 28 cruise. The anomaly was characterized by increased baseline stabilization (BLS) voltage and increased SSI input current. The initial problem was cleared via real-time commands to disable the light flood circuitry, which floods the CCD via LED's to erase the previous image. This problem recurred several times during the Ganymede 29 encounter in December even though the light flood remained disabled throughout the encounter sequence indicating a more complex failure mechanism. The behavior was cleared twice by commanding a power cycle and a memory reload, however, it also cleared autonomously several times. Images acquired while the camera is in the anomalous state are completely saturated.

The failure has been localized to the sample and hold circuitry, either in an opamp or a JFET, and was most likely induced by radiation. The cause of the failure and the exact trigger to go into or out of the anomalous state remains unknown. The light flood is not thought to be the source of the anomaly but is a trigger; testing shows that the signal chain magnitude, which might aggravate the problem, only slightly increased with the light flood enabled. At the request of the camera team, real-time commands were sent in May 2001 to turn on the light flood. In the following 7 hours, 13 separate anomalous periods were detected in the camera voltage and input current. The nominal camera state was re-established by turning off the light flood and power cycling the instrument.

To protect high priority science and to mitigate thermal damage to the vulnerable part of SSI circuitry, which heats very rapidly in the anomalous state, the camera is now power cycled either by the background sequence before significant observations or as a real-time response to anomaly detection. A new, faster memory reload method was developed during Ganymede 29 cruise in which a copy of the SSI flight software is stored in CDS memory and a power cycle/software reload (PCR) is invoked by two commands from either a stored sequence or from the ground. During Callisto 30 encounter, three SSI PCRs were placed in the background sequence; three more were sent real-time, in response to the recurring BLS anomaly (See Section 7.3).

Further testbed testing and circuit diagram evaluation by the instrument engineer suggested that disabling the erase mode (in addition to the flood mode) might mitigate the problem by reducing the video signal dynamics and keeping it from saturating. The risk was a possibility of residual images. The I31 encounter was designed to have the erase mode disabled during the majority of images; however, a period of vulnerability remained when the memory reload initializes the camera with erase mode enabled. At Io 31, the camera entered the anomalous state during a PCR just prior to closest approach, and was recovered via a real-time PCR at 14 R_J outbound (See Section 7.5). The reload process is currently being redesigned to remove the vulnerability by preventing the camera from entering erase mode. In addition, a conditional check will be performed so that the reload process will only execute if the camera is in its anomalous state.

5.2 Other Instruments' Status

EPD continues to experience transient memory problems near closest approach. Sequenced memory reloads are now placed in each encounter sequence to minimize loss of data and real-time recovery efforts. The Ganymede 29 and Callisto 30 sequenced reloads each were necessary; no real-time commands were needed to recover the instrument. In Io 31 two reloads were sequenced, including a partial quick reload just before closest approach, however neither one was necessary as the instrument has experienced no memory upsets during that encounter.

NIMS's grating remains stuck[5], and sequenced memory reloads continue to be needed to preclude loss of data due to memory corruption. Memory glitches occurred once in Ganymede 29 and twice in Io 31, while none occurred in Callisto 30.

UVS is no longer being operated[5], and has remained off during the past three encounters. Potential annealing was tested during G28 cruise, after the instrument had been powered off 222 days. The grating was still uncommandable.

The other science instruments (PWS/PLS/HIC/DDS/PPR/MAG/EUV) have had no change in their operating status in the past year.

6. Sequence Operations in GMM

As mission operations continued during this fifth year of orbital operations at Jupiter, much of the focus was on maintaining capabilities as the flight team continued to decrease in size. The three most significant challenges to operations were the scope of the Ganymede 29 encounter and the associated collaborations with the

Cassini flyby of Jupiter, the operations support needed in order to gather a continuous sample of the magnetosphere from October 2000 to February 2001, and preparations for returning to the high-radiation environment near Io.

Because of the presence of the Cassini Spacecraft near Jupiter in December 2000, there were an unusually large number of diverse science objectives for the Ganymede 29 encounter (See Section 7.2). The result was a plan for science observations that was more like many of the Prime Mission encounters than the limited scope of most extended mission flybys. The required level of activity was supportable because of an experienced operations team and because the long-period orbits (5-7 months) that followed Ganymede 28 and 29 encounters allowed sequences to be developed in series (only a single command sequence in active development at a time).

The desire to collect an ~100-day long continuous magnetospheric survey presented a different type of problem. During Prime Mission, similar duration real-time science (RTS) surveys were supported by having near-continuous Deep Space Network (DSN) coverage. Given the increased number of planetary and Earth-orbiting missions, continuous DSN coverage of Galileo was not possible for extended periods. During RTS data collection, any gaps in DSN coverage longer than 7.5 hours cause overflow of Galileo's onboard data buffer (the multi-use buffer, or MUB). During Prime Mission, the standard procedure for dealing with overflows was to record the buffered data to tape for later playback. These recordings are referred to as "buffer dumps." However, this process was used infrequently in extended mission operations (6 times in 15 orbits) and never interleaned with playback because of its sensitivity to any changes in DSN station allocations and the labor-intensive process required to establish or change the timing of buffer dumps. In addition, buffer dumps are an inefficient use of downlink telemetry resources. Using standard procedures for returning buffer-dumped data commonly uses two to three Mbit of downlink to return each one Mbit of RTS data.

To obtain the desired magnetospheric survey under the constraints imposed by extended mission operations, a new technique was developed to allow RTS and buffer dumps to be collected while data playback operated concurrently. By establishing a set of rules and then coding them into a ground software tool, the Flight Team was able to quickly generate and update commands to collect RTS data and to reposition the tape to play back previously-recorded buffer dump data when DSN resources were available, and record new buffer dumps when downlink was not available. This new process was utilized during the last 61 days of the Ganymede 28 cruise sequence. During this time, 83 buffer dumps were required, 70 of which were palyed back prior to the star of recorded observations for the Ganymede 29 data. The net result was approximately 35 Mbit of exra capability for Ganymede 28 data return, the equivalent of approximately 60-70 imaging camera frames, or 20 days of fields and particles RTS data.

The final challenge to operations during the past year was that represented by the Io 31 flyby. In the Io 24 and Io 25 encounters, spacecraft safing events interrupted data-gathering activities at encoutner[5]. In the Io 27 flyby, a safing event occurred after most data-gathering activities had completed, decreasing the total amount of data that could be returned[5]. While the creatio of an error-free command sequence for the Io 31 encounter took first priority, the Flight Team also found time to develop a pair of contingency sequences. The first was a small sequence which could reside in memory reserved for orbital trim maneuvers (OTMs). The small contingency sequence was designed to allow Galileo to capture fields and particles data to tape for one hour centered on closest approach. This recorded data would fulfill our primary science goal for the flyby: determining whether Io possesses an internally-generated magnetic field. The small contingency sequence could reside in memory while the nominal encounter sequence operated and could be started by a very short command sequence from the ground. It was also robust to several possible post-safing configurations of the spacecraft, meaning tat it could be sent at the last possible commanding opportunity (approximately 2 hours prior to Io closest approach) with minimal safing recovery.

The second contingency sequence was a truncated version of the nominal science sequence. It was designed to begin execution in time to allow for the high-priority observations beginning approximately 30 minutes prior to closest approach, and continue for approximately 12 hours. Similar contingency sequences were used in both the Io 24 and Io 25 flybys, allowing recovery of much of the near-Io observations. This contingency was designed for cases in which any spacecraft problems occurred multiple hours prior to closest approach, such time was available to place the spacecraft in its nominal configuration prior to the beginning of the contingency sequence. Fortunately, neither contingency sequence was needed and observations throughout the Io 31 encounter went largely as planned (See Section 7.4).

7. Summary of Encounters in the Past Year

Most of the past year of Galileo operations has been taken up by the Cassini Phase of the GMM, so-called because of the planned collaborative observations of the Jovian system by Galileo and Cassini which occurred for a nearly four-month-long period centered on Cassini's closest approach to Jupiter on December 31st, 2000. The primary science goals of the joint Galileo-Cassini observations were to:

- Study how interactions with the solar wind affect the dynamics and structure of Jupiter's magnetosphere, including the Jovian auroral regions.
- Significantly improve understanding of the dynamics of Jupiter's atmosphere, particularly with regard to active storm regions.
- Observe Io while in eclipse in order to investigate airglow phenomena and monitor hotspot activity.
- Study the dynamics of Jovian dust streams using near-simultaneous measurements of a particular dust stream from both Galileo and Cassini.

In addition to these joint goals, there are several unique opportunities afforded to Galileo during this phase of operations. The primary science goals for stand-alone Galileo science were to:

- Study the dynamics of the largely unexplored dusk sector of the magnetosphere.
- Understand the dynamics of Ganymede's unique magnetosphere.
- Study key features at very high resolution to understand the relative importance of tectonism and volcanism in forming Ganymede's surface.
- Determine particle sizes in the various ring components of the Jovian ring system.
- Study the storm system dynamics represented by the recently-merged white ovals in Jupiter's atmosphere.

Science observation strategies similar to those used during Prime Mission and GEM were utilized to obtain visible, infrared, and polarimetric remote sensing measurements of Jupiter and Ganymede (and other satellites). Fields and particles instruments obtained data on the electromagnetic fields and particle radiation inside and outside the Jovian magnetosphere as well as inside Ganymede's unique magnetosphere. Tracking of Galileo's radio signal during a near-occultation by Jupiter was used to obtain ionospheric sounding data of the northern polar region of Jupiter.

7.1 Cruise Science Inbound to Ganymede 29

After the Ganymede 28 encounter on May 20, 2000, Galileo began its longest cruise period, or period between satellite encounters. For the next three and a half months, Galileo receded from Jupiter, reaching apojove on September 8, 2000 at slightly more than 290 R_J (20.7 million kilometers) from Jupiter. As Galileo began to fall inward toward Jupiter and a December flyby of Ganymede, the Cassini spacecraft was also nearing Jupiter.

In contrast to previous orbits during the Galileo extended missions, science activities began long before the spacecraft reached the vicinity of the Galilean moons. On October 26, 2000, while Galileo was still over 200 R_J (14 million kilometers) from Jupiter, the six fields and particles instruments (DDS, EPD, HIC, MAG, PLS, and PWS) began collecting real-time science (RTS) data (See Figure 5). For the next 100 days, these instruments would collect a continuous swath of magnetospheric data, using an operations strategy that combined real-time downlink with data buffering via the onboard tape recorder (See Section 6). This swath began in the solar wind and continued through the bow shock and magnetopause transitions, into the outer, middle, and inner portions of the magnetosphere, and then back out, ending in the solar wind. During this time, Galileo was able to measure numerous transitions through the Jovian bow shock and magnetopause as the magnetosphere expanded and contracted in response to changing conditions in the solar wind, and as Galileo first approached and later receded from Jupiter.

The data were gathered with two basic goals in mind. The first was to obtain a continuous sample of the Jovian magnetosphere along the dusk sector, which is critical to understanding the dynamics of the Jovian magnetosphere. The second goal was to utilize the presence of a pair of uniquely capable spacecraft, both in the vicinity of Jupiter, to simultaneously measure properties of the solar wind as well as the behavior of the magnetosphere. By using Cassini's magnetospheric instruments to measure activity in the solar wind and Galileo's to measure activity inside the magnetosphere (See Figure 5), it would become possible to begin to understand the extent to which exterior forcing by the solar wind affects the dynamics of the interior of the magnetosphere. By the start of the Ganymede 29

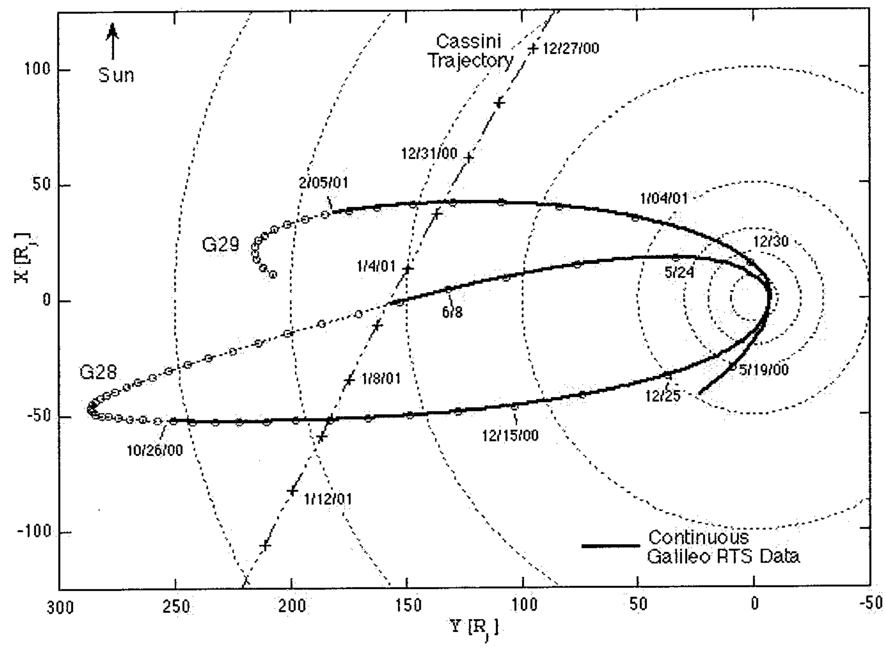

Figure 5. Galileo and Cassini Joint Observation Trajectories

encounter sequence, the fields and particles instruments had collected 61 days of continuous RTS data, covering the region between 200 and 50 R_J (14 million to 3.6 million kilometers) from Jupiter.

7.2 Ganymede 29

The fourth satellite encounter of the Galileo Millennium Mission occurred on December 28, 08:25 UTC at an altitude of 2,337 km above the surface of Ganymede. At the time of closest approach, Ganymede was in darkness, eclipsed by Jupiter between 08:10 and 09:59 UTC. The encounter sequence was longer than usual so as to include the outbound portion of the Galileo/Cassini magnetospheric survey (See Figures 6a, 6b). It began at 22:30 UTC on December 26 and continued until 20:00 UTC on February 5, 2001. Although nominally a Ganymede encounter, the science observing plan for this encounter was diverse. Remote sensing data were gathered for all four Galilean moons, storm regions in the Jovian atmosphere, the Jovian auroral zone, and the rings. Fields and particles instruments gathered data on the Ganymede magnetosphere, Jupiter's magnetosphere, and made measurements of the Io-related dust streams.

The first observation of the sequence occurred during the Earth occultation by Jupiter. Tracking of Galileo's radio signal during the occultation, which grazed the northern polar regions of Jupiter's atmosphere, allowed the Radio Science Team to obtain electron density profiles, and compare them to measurements made of the southern hemisphere earlier in Galileo's mission.

Shortly after the occultation period ended, the fields and particles instruments collected a one-hour high-resolution recording centered on Ganymede closest

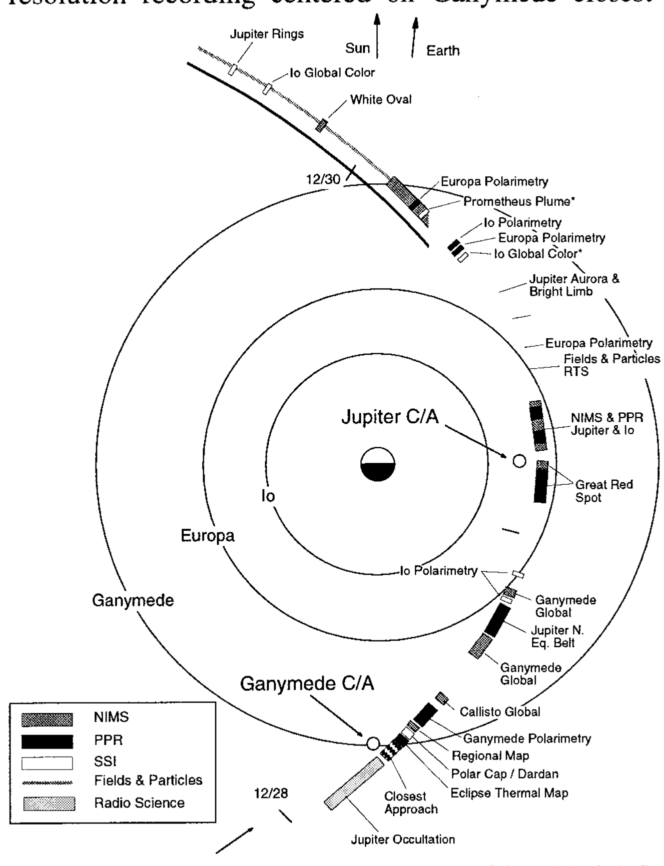

Figure 6a. Ganymede 29 Encounter Trajectory

approach (See Figure 6b). These data show the interactions between the Jovian magnetic field and the Ganymede's magnetosphere. In addition, one minute of high-rate PWS data was collected at closest approach in order to measure chorus emissions (observed in previous Ganymede flybys). For the remainder of the encounter sequence, fields and particles RTS data were collected and either downlinked in real time or stored to the onboard tape recorder (See Section 6). In collaboration with the Cosmic Dust Analyzer (CDA) instrument onboard Cassini, DDS collected data on dust stream particles originating at Io and flung outward from Jupiter by the magnetic field.

PPR observations also began during the Ganymede closest approach period. Taking advantage of the eclipse period, PPR was able to collect observations showing the cooling of the surface during the nearly two hours of darkness, and then observe surface warming over a variety of different terrains after the eclipse (See Figures 6a, 6b). Other Ganymede observations included regional scans to obtain thermal intertia data, and a scan of the northern polar region to determine temperatures and see if exotic volatiles might collect there. During the next several days of the encounter, PPR also obtained a series of atmospheric observations, examining the Great Red Spot (GRS), the Northern Equatorial Belt, and a high-resolution observation of a 5 μm hotspot. Several observations were planned jointly with the Cassini CIRS (Composite Infrared Spectrometer) instrument team. CIRS was able to obtain more spatial coverage over a longer time period, while PPR supplied data at longer wavelengths and at twice the spatial resolution. PPR also continued its campaign of polarimetry observations, obtaining unique phase angle coverage of Io and Europa.

SSI observations during Ganymede 29 included a diverse set of objectives, including observations of the surfaces of Ganymede and Io, the atmosphere of Jupiter, and the Jovian ring system. Observations of Ganymede began with an attempt to image a possible Ganymede aurora while the moon was in eclipse. This was followed by regional-scale images obtained to fill gaps in coverage

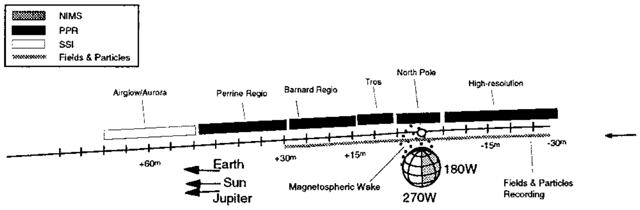

Figure 6b. Ganymede 29 Flyby Geometry

and to observe the polar cap boundary region. Io observations included global-scale color imaging designed to monitor changes due to continuing volcanism, a Prometheus plume observation, and a series of images of Io while in eclipse. The eclipse images were part of a joint activity with Cassini's imaging camera, and were designed to look at hotspot and auroral activity. A feature track activity was designed as a series of fourteen observations which tracked changes in a particular storm region over several rotations of Jupiter. A series of ring observations were also designed to yield information on the vertical structure and particle sizes of the Jovian rings.

During the encounter itself, after the Ganymede observations, SSI suffered a series of recurrences of the BLS (baseline stabilization) anomaly, first observed during the Ganymede 28 cruise period in July 2000 (See Section 5.1). Commands were sent to redundantly disable the light flood, then to place the camera in a specific mode in which the light flood was disabled, and finally to power cycle the instrument and reload its flight software. The first two commands appeared to have no effect, but the last temporarily returned the camera to nominal status. Although anomalous telemetry was detected later, it returned to nominal readings before any commands could be sent. In all, five anomaly episodes were observed between December 29, 2000 and January 2, 2001. All images taken during anomaly periods were found to be saturated and contained no useful data. Io observations were heavily affected, although one of the two Io global images that were obtained showed the presence of a new volcanic plume deposit surrounding the Tvashtar region, a locus of extremely active volcanism during GEM and GMM (See Section 8.3). Approximately half of the Jupiter atmospheric observations were also affected, while those of Ganymede and the ring system were unaffected.

NIMS observations during Ganymede 29 included an extensive campaign of Jupiter atmospheric data-taking, much of it in collaboration with Cassini's VIMS (Visual and Infrared Mapping Spectrometer), as well as observations of all four Galilean moons (See Figure 6a). NIMS observations began with a regional observation of Ganymede for compositional analysis, followed by a global mineralogical map. Distant observations were performed for Callisto, Europa, and Io in order to assist in calibration of VIMS data. The Io observations were also designed to monitor hotspot activity or other changes on the surface in preparation for upcoming Io 31, Io 32, and Io 33 flybys. Jupiter observations included a series of global mapping mosaics, comprising pole-to-pole spectra of all longitudes and used to provide compositional and dynamical information. Focused observations were also obtained for the wake region near the Great Red Spot (GRS), the single remaining white oval, the Northern Temperate Zone, and several 5 µm hotspot regions. In addition, data were obtained for the southern auroral oval region to examine spectral characteristics of the auroral discharge.

Nominal playback of the Ganymede 29 data began at the end of the magnetospheric survey on February 5, 2001. Prior to that, in early January, small portions of several SSI images were played back in order to assess the affect of SSI anomaly episodes on SSI data. Nominal playback was stopped on April 22 so that SSI and NIMS could perform recorded calibrations. These were the first such calibrations for these two instruments since the Callisto 9 orbit during Prime Mission (July 1997) and probably the final opportunity for this detailed calibration. Playback of the combined magnetospheric survey, Ganymede 29 encounter data, and calibration data ended on May 21, slightly more than a day prior to the beginning of the Callisto 30 encounter sequence.

7.3 Callisto 30

The Callisto 30 encounter (Figure 7a) marks the beginning of the Io phase of the GMM. During this phase, Galileo will make a close flyby of Callisto (C30), using its gravity assist to lower perijove and to set up two polar flybys and one equatorial flyby of Io. The primary science goals during the Io phase are to:

- Investigate the apparent discrepancies in impact crater populations at various scales on Callisto. Establish the implications for the outer solar system crater flux and surface ages of the Galilean satellites.
- Increase insight into high temperature and high volume volcanic eruptive processes on Io, particularly as they relate to ultramafic (e.g., komatiitic) and flood basalt volcanism on the early Earth.
- Determine the nature of Io's magnetic field and characterize Io's internal dynamics and energy balance. Better constrain global heat-flow measurements as bounds on tidal heating models for Io and Europa.
- Characterize the plasma acceleration processes in the unexplored afternoon sector of the dayside. Clarify the dynamics of the Jovian plasma sheet and its role in overall dynamics of the magnetosphere.

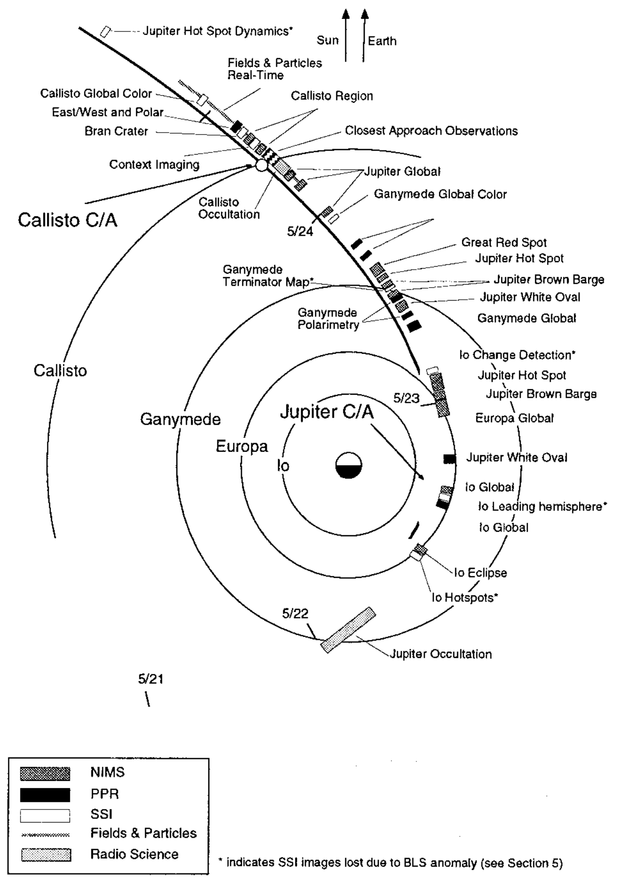

Figure 7a. Callisto 30 Encounter Trajectory

- Establish properties of plasma transport processes such as interchange and diffusion in the outer part of Io's plasma torus. Gain insight into sources and sinks for torus materials near Io.

Science observation strategies did not change markedly during this phase of GMM. All instruments (except UVS[5]) continue to collect data at appropriate opportunities. With the notable exception of SSI (See Section 5.1), there have been no significant changes to spacecraft or instruments that would require altering observation strategies.

The fifth encounter of the GMM and the final Callisto encounter of Galileo's tour at Jupiter occurred on May 25, 2001 at 11:24 UTC. In this closest of Galileo's flybys, the spacecraft passed within 138 km of the surface of Callisto. The flyby was unusual in that the spacecraft approached Callisto along the umbral shadow cast by this moon (See Figure 7b). For nearly an hour and a half prior to closest approach, Galileo was in shadow, and for an hour Callisto also blocked the line-of-sight to Earth. At the 9.7 km/sec velocity of the flyby, it required slightly more than 8 minutes for the spacecraft to transit the disk of the moon itself.

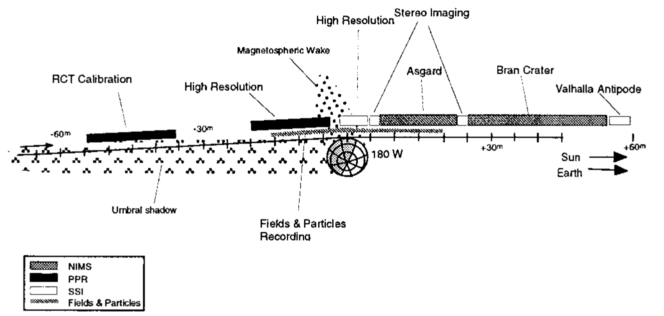

Figure 7b. Callisto 30 Flyby Geometry

The geometry of the flyby was dictated in large part by GMM tour design. A Callisto encounter was an efficient way to decrease the periapsis of the orbit and allow Galileo to return to Io. By placing the Callisto flyby after perijove (See Figure 7a), that change did not occur in the current orbit, but rather in the subsequent encounter, sparing the spacecraft a passage through the high-radiation region near Io's orbit.

The Callisto 30 encounter sequence began at 17:00 UTC on May 22, 2001 and continued until 23:30 UTC on May 27, lasting slightly more than five days. The first observation of the sequence was a Radio Science occultation experiment, as the spacecraft passed behind Jupiter as seen from Earth. The experiment lasted approximately 2.5 hours and collected data at northern latitudes, and with the spacecraft close to Jupiter. This provided both unique latitudinal coverage and improved results for the lower ionosphere. In addition, Radio Science was also able to obtain data during the Callisto occultation measuring the vertical distribution of free electrons in the Callisto ionosphere.

The fields and particles instruments began their observations with an 18 hour long period of RTS data collection, beginning six hours prior to perijove. Because of limitations on downlink capability in this orbit (see below), RTS data collection was halted and then restarted 7.5 hours prior to the Callisto flyby and continued for almost two days (Figure 7a). The other fields and particles observation was a 35 minute recording of high-resolution data at Callisto closest approach (See Figure 7b). The recorded data was obtained to allow further investigation of Callisto's induced magnetic field (discovered during Prime Mission) and to allow possible measurements by PLS of Callisto's surface-bound exosphere.

NIMS observations during the encounter were focused on Jupiter and Callisto, but also included distant Io and Europa observations. Targets on Callisto itself were chosen to be complementary to those seen in Prime Mission, or so as to complete coverage of specific regions such as Bran Crater and the Asgard Basin. A primary objective of these observations was to map compositional variations across the surface. Jupiter observations were targeted at continuing studies of cloud dynamics by looking at the GRS wake region, a region of possible "brown barges," and a region of 5μm hotspots. At least two views of each feature were obtained over 2-3 Jupiter rotations. Three global mapping observations were made to complete NIMS global coverage of Jupiter's atmosphere. Io observations were made both in daylight and with Io in eclipse in order to monitor volcanic activity, detect changes in SO_2 distribution, and refine temperature measurements of Io's surface.

PPR also collected a diverse set of observations, including Jupiter, Io, Ganymede, and Callisto. During the flyby of Callisto, PPR collected east-west scans across the terminator in order to obtain surface thermal inertia and observe changes in temperatures as portions of the surface began to be warmed by the Sun. Another observation measured temperatures at the polar regions, looking for the possibility of exotic volatile species there. Jupiter observations included PPR's highest-resolution views of temperature near the 300 millibar level, which are used to constrain global convection and energy transfer models, as well as a scan of the single remaining white oval. Finally, PPR also completed their map of dayside temperatures on Io, and obtained a nightside temperature map and added to polarization measurements of Ganymede.

SSI observation plans for Callisto 30 were focused on Callisto but also included imaging of Jupiter, Io, and Ganymede, as well as an observation of Amalthea which was included primarily to assist with the planning for Galileo's flyby of that minor moon in November 2002. Due to two recurrences of the BLS anomaly (see below), all imaging of Jupiter, Io, and the Amalthea image were lost. One of two Ganymede observations, and all Callisto images were obtained successfully.

At Callisto, SSI recorded its first global-scale color image of the leading hemisphere of the moon as well as several extremely high-resolution (≤10 meters) images of the near-terminator region. Moderate-resolution (100's of meters) images were obtained as context for the high-resolution frames. Images were obtained at similar scales for the region antipodal to the Valhalla impact basin in order to look for "weird terrain." Such terrain would be analogous to the heavily disrupted surface observed on Mercury by Mariner 10, antipodal to the Caloris impact basin. A global-scale color image was successfully obtained for Ganymede, filling the last remaining gap in such coverage. An observation of some unusual craters and tectonic features made at favorable sun angles was lost due to the BLS anomaly. Other notable loses included Io color and eclipse imaging. One of the Io observations was designed to look for evidence of ongoing plume activity in the Tvashtar region, seen by Galileo and Cassini during the Ganymede 29 encounter (See also Section 8.3).

In order to mitigate the problems seen during the Ganymede 29 encounter, three power cycle/software reloads (PCRs) of SSI were included at key points in the Callisto 30 encounter sequence (See Section 5.1). The first was placed near perijove, and was designed to protect Io and Amalthea observations. The second and third were placed just before and immediately after the Callisto flyby, in order to protect Callisto and Jupiter imaging. In the course of the encounter, the instrument entered its anomalous state near the time of the first image. Neither the first PCR nor a PCR sent via real time command was successful in restoring function. A second real-time PCR was sent during a command opportunity between two Ganymede observations and was successful. The anomaly recurred after the completion of all Callisto imaging and prior to the planned Jupiter observation. Nominal status was restored by sending a third real time PCR (the sixth overall of the encounter), but the commands could not be sent until it was too late to recover SSI for its Jupiter observations.

Playback of Callisto 30 encounter data occurred over the next two and a half months. Playback began with a preview of SSI image data in order to gather any additional information on the BLS anomaly. Between June 4 and June 24, Galileo was effectively out of contact due to solar conjunction and no data were played back. After the preview pass completed, a nominal playback strategy was used to bring back remote sensing and fields and particles data. Because of solar conjunction and increasing competition for 70-meter DSN antenna resources, the total data return for Callisto 30 was quite limited, with only about 40 Mbit of science data returned.

7.4 Io 31

The sixth encounter of the GMM and the first of three consecutive Io flybys occurred on August 6, 2001 at 04:59 UTC, when the spacecraft flew within 194 km of the surface of Io (Figure 8a, 8b). This was the first flyby by Galileo to be accomplished without any DSN tracking coverage for several hours before and after closest approach. With the Madrid 70-meter antenna down for upgrades to support future missions, no 70-meter antennas had Galileo in view at the time of the flyby. In addition, the near-polar geometry of the flyby (Figure 8b) brought the spacecraft almost directly over the Tvashtar region. Galileo and Cassini had observed a volcanic plume centered on this region in December 2000 (See Section 8.3). Galileo's trajectory would cause the spacecraft to fly through the upper portions of this plume, if it were still active at the time of the flyby. Galileo approached Io from the night side, flying almost directly across the terminator at the closest approach point (78°N, 172°W), and looking back at the fully lit

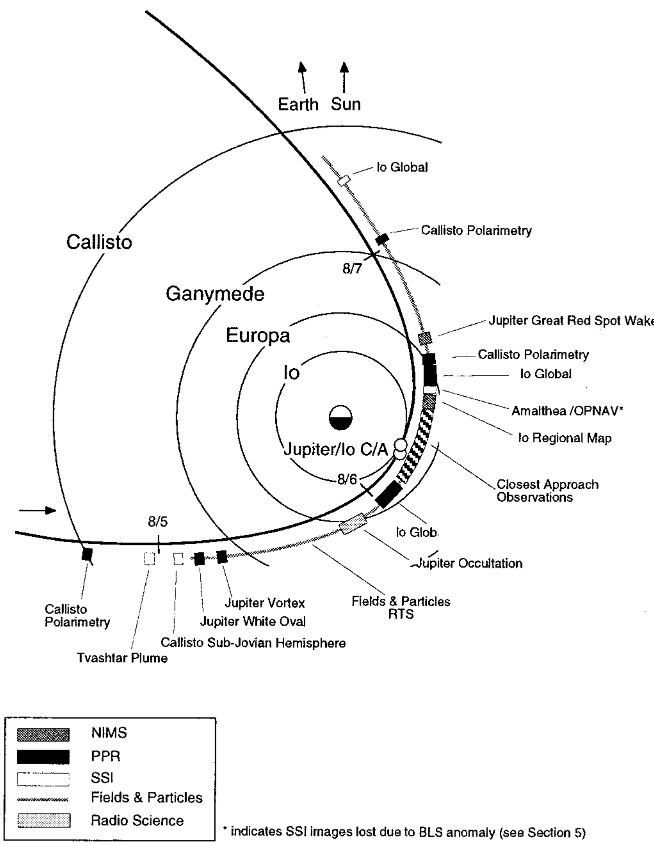

Figure 8a. Io 31 Encounter Trajectory

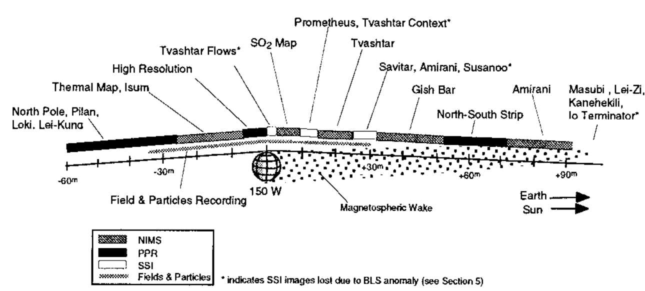

Figure 8b. Io 31 Flyby Geometry

disk as the spacecraft recedes from Io.

The Io 31 encounter sequence began at 11:00 UTC on August 4, 2001 and continued until 21:00 UTC on August 9, lasting approximately 5.5 days. The majority of science activities for this period were focused on Io itself, with additional observations of Jupiter's atmosphere, Callisto, and Amalthea also included.

The first observation of the sequence was a polarimetry observation of Callisto's surface by PPR, one of several taken at various phase angles during the encounter. Jupiter observations included continuing coverage of the single remaining white oval, as well as observations of the North and South Vortex regions. The latter set is designed to observe the polar regions, where Earth-based observations suggest a wave-like boundary seen near the pole. Measurements of this region may yield information about the dynamics of the polar atmosphere. An extensive campaign of Io observations includes night-time observations of the full disk at low resolution and of selected regions at high resolution. Of particular interest are temperature measurements of the polar region, which have been found to be warmer than expected in previous flybys. PPR will collect detailed scans across the volcano Loki and Lei-Kung Fluctus, a large lava flow, and will obtain its first global map of daytime temperatures while looking back at Io after closest approach.

NIMS observations for this encounter were focused almost exclusively on Io, except for a two-part observation of the turbulent wake region near Jupiter's Great Red Spot, designed to study cloud dynamics. Prior to closest approach, NIMS obtained thermal IR measurements of the region near Pele and Pillan volcanoes and in the Isum region in order to look for changes and new volcanic activity since the Io 27 flyby in February 2000. A planned map of SO_2 distribution at high northern latitudes had to be significantly reduced during sequence development (See Section 5). Shortly after closest approach, NIMS obtained several high-to-moderate resolution observations of targeted regions, including Tvashtar Catena, the region near Prometheus and the Emakong lava flow, Amirani, Maui, and Gish Bar, and a newly-active hotspot region in the southern hemisphere, first detected in data from the Callisto 30 encounter.

SSI observations during Io 31 began with a set of distant images of Io designed to detect any ongoing plume activity in the Tvashtar region (See Section 8.3). Gas-rich plumes like Tvashtar are difficult for SSI to detect because of its limited sensitivity in the UV, so it is uncertain if there will be any direct detection of a plume even once the data are played back between mid-August and early October. Non-Io observations by SSI included a view of the sub-jovian hemisphere of Callisto, a feature track observation to measure propagation of mesospheric waves in the Jovian atmosphere, and two Amalthea images. The Amalthea data will also be used to refine estimates of Amalthea's orbit in preparation for the planned flyby in November 2002. Observations of Io include global color monitoring of changes to the surface, high-resolution imaging at Tvashtar, and moderate-resolution images at a variety of regions, including Masubi, Lei-Zi, and Kanehekili Fluctus, the Amirani/Maui region, Savitr and Itzamna Patera, and the region near the newly-discovered southern hemisphere hotspot (see above). Observations at moderate resolution have been found through experience to provide an excellent balance between the detail required to understand the processes that shape Io's surface, and the broader views necessary for understanding geologic context and for discovering new or unexpected features.

In order to maximize the chances that SSI would successfully obtain as many of the planned observations as possible, two actions were taken for Io 31. Eight times during the sequence, SSI PCRs were issued, placed so as to maximize the protection of planned science observations. In addition, the instrument commanding strategy was altered to turn off the camera's erase cycle, which executed approximately once per minute while the camera was turned on. These measures were only partly successful. Observations of Callisto as well as plume-detection imaging of Io were successfully obtained early in the encounter sequence, at distances greater than 20 R_J. All observations taken in the vicinity of Io, from shortly after closest approach itself (at 5.9 R_J) through the second of two Amalthea observations (at ~7 R_J) were unsuccessful due to recurrence of the BLS anomaly. Commands were sent in real time to perform a PCR at the first available opportunity, executing while the spacecraft was at ~ 14 R_J. These returned the camera to the nominal state, allowing all Jupiter observations and a pair of global color observations of Io to be recorded successfully.

Fields and particles observations during the encounter included nearly 2.5 days of RTS data collection, beginning at 05:15 UTC on August 5 (~17 R_J inbound) and ending at 06:30 on August 7 (~23 R_J outbound). RTS data are obtained in order to monitor the behavior of the inner magnetosphere of Jupiter and provide context for any high-rate, recorded data. The length of this observation was restricted by the limited DSN tracking coverage that was available during this time. The fields and particles instruments also obtained nearly 64 minutes of high-resolution data at Io closest approach, from 04:25 UTC to 05:29 UTC on August 6, beginning slightly more than 33 minutes prior to closest approach. This fulfilled one of the primary science goals of the Io phase of the GMM mission extension by obtaining a near-polar measurement of Io's magnetic field. In addition, the geometry of this pass was a significant opportunity for measuring interactions between the Io torus plasmas and Io itself, as well as the properties and dynamics of the Io flux tube.

Playback of Io 31 data included an initial SSI data preview pass through the tape. This was done in order to verify which SSI observations were successful and was followed by the standard two passes through all recorded data. Playback began on August 8 and will continue until early October. Currently, the Galileo Project is examining how to best optimize the science data return during the Io 31 cruise period. Additional science activities may be added to the cruise period, similar to Io 24[5].

8. New Scientific Discoveries

8.1 Delta Velorum, A Variable Star

One of the more unusual findings by Galileo was the co-discovery that Delta Velorum, one of the 50 brightest stars in the sky, is also a variable star[7]. In June 2000, during the Ganymede 28 cruise period, one of the three stars being used by Galileo's star scanner was temporarily "lost." There was initial concern about the functioning of the star scanner itself, but no problems existed with identification of any other stars. The star scanner was also able to reacquire the "lost" star (Delta Velorum) after about 8 hours. Because the star scanner identifies stars primarily on the basis of brightness, variable stars are not used for Galileo's navigation. A member of the Galileo flight team, wondering if Delta Velorum might be mis-identified in the standard star catalogs, forwarded a report of the incident to the American Association of Variable Star Observers. Using data from Galileo, which showed additional instances of dimming of Delta Velorum, amateur astronomers were able to verify and then predict that Delta Velorum, which is actually a tight group of at least five stars, contained an eclipsing binary. The two stars mutually eclipse one another for only a few hours every 45 days, which probably accounts for the fact that its variable nature was not recognized previously.

8.2 A Subsurface Ocean at Ganymede

A major discovery of Galileo's Prime Mission was that Ganymede possesses an internally-generated magnetic field. Although there were no Ganymede flybys during the two year long Galileo Europa Mission (1998-1999)[3], analysis continued on both the images of the surface of Ganymede and on the fields and particles data obtained during Ganymede flybys. These data suggested that Ganymede might have a history more similar to Europa than had been previously thought. In particular, images seemed to indicate that ice volcanism had created similar landforms to those seen on Europa, while magnetic field data indicated that Ganymede, like Europa, might possess an induced magnetic field.

An induced magnetic field is generated whenever a conductive material is placed in a magnetic field. In the case of Europa, the most plausible model for the conductive material is a water layer at least several kilometers thick, within approximately 100 kilometers of the surface. This induced field is thought to be one of the strongest pieces of evidence to support the idea that liquid water is currently present beneath Europa's icy surface. For Ganymede, the magnetic signature is complicated by the presence of an internally generated field. Data collected by the magnetometer instrument during the Ganymede 28 flyby were compared with data from previous flybys. They indicate that some conductive material is present, and are consistent with the presence of a salty water layer a few kilometers thick, located within 200 kilometers of Ganymede's surface.

8.3 Plume Activity at Tvashtar Catena, Io

Images of the Tvashtar Catena region of Io obtained during the Io 25 (November 1999) and Io 27(February 2000) flybys showed evolving volcanic activity in that region. During the joint Galileo-Cassini flyby of Jupiter in December 2000, both spacecraft concentrated a significant number of observations on Io. The data revealed that a volcanic plume was erupting from the Tvashtar region.

Evidence for the plume eruption was found in both Galileo and Cassini images of Io. A global-scale image of Io obtained by the SSI instrument on Galileo revealed a freshly-deposited ring of reddish material approximately 1,400 kilometer in diameter, centered on Tvashtar. Such deposits are indicative of plume activity. The most prominent of these reddish rings is the one surrounding the Pele eruptive center, near Io's equator. In general, plume eruptions have been observed to fall within mid- to low-latitude regions, and have not commonly been seen in the polar regions (Tvashtar is located near 70° N). Observations of Io using the Cassini imaging camera's UV filter were able to directly detect the plume, revealing that plume gases reached altitudes of nearly 400 km above Io's surface.

9. Future Plans

A final extension of the Galileo Millennium Mission has been approved by NASA Headquarters to continue investigation into key outstanding science questions concerning Io and the inner Jupiter system and to properly dispose of the spacecraft by controlled impact into Jupiter. Figure 9 shows a timeline for the final phase of the Galileo mission.

9.1 Io 32

The next Io encounter will be a south polar pass on October 16, 2001 01:25 UTC, at an altitude of 177 km. This flyby provides a second opportunity to characterize Io's magnetic signature and refine the magnetic field model with its implications for the internal structure of the moon. Remote sensing instruments will primarily concentrate on near terminator topographic imaging, high resolution observations of the southern polar region, and continued monitoring of known active volcanic centers, including Tvashtar and Pele. Jupiter hot spots will also be observed. Fields and particles instruments will obtain high resolution data in the Io torus as part of the ongoing study of the dynamics and structure of Jupiter's inner magnetosphere.

9.2 Io 33

The final Io flyby will be a northern mid-latitude pass on January 17, 2002, 14:08 UTC, at an altitude of 100 km. Although this encounter is designed to place the spacecraft on a ballistic trajectory to impact Jupiter two orbits later, it also presents outstanding targets of opportunity for science. Particles and fields instruments will continue their characterization of the Io torus and magnetic field. Acquisition of remote sensing and radio science will be planned , however, as of this writing, resources to return and process the data have not been identified. The unique geometry of this pass presents the best opportunity in the entire mission for high-resolution observations of the Jupiter facing hemisphere of Io.

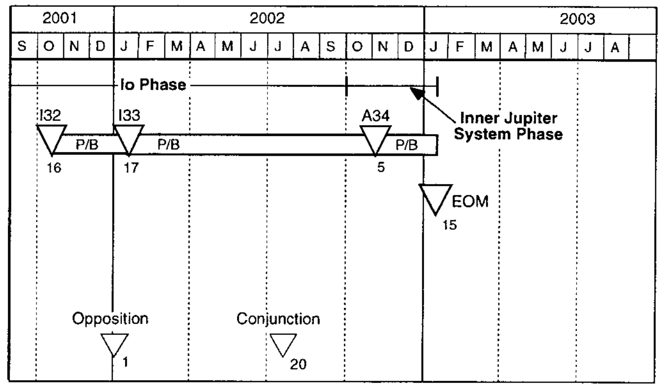

Figure 9. Galileo Final Phase Timeline

9.3 Amalthea 34

The final encounter of the Galileo mission is also a first as the spacecraft flies by Amalthea, one of the small inner moons, on November 5, 2002, 19:39 UTC with a goal of measuring the mass, and thereby the bulk density, of this minor moon. This passage through the jovian system will take Galileo within two Jupiter radii of the planet, through the gossamer rings, and into the inner magnetosphere, a region analogous to the Earth's plasmasphere and trapped radiation belts. No remote sensing is planned for this orbit, but extensive recorded and RTS data sets will be obtained by the fields and particles instruments during this unique encounter. Mission operations will end January 2003 with the return of the Amalthea 34 recorded data.

9.4 Jupiter Impact

The end of Galileo's historic journey is scheduled for September 21, 2003 as the spacecraft plunges into the atmosphere of Jupiter. Disposal of the spacecraft, as mutually agreed upon by the Project and NASA Headquarters, is necessary for planetary protection purposes: a result of the mission's own success. Evidence for the existence of liquid water on Europa raises the possibility of life on that frozen moon. The planned destruction of Galileo removes any risk of forward contamination of Europa by an inadvertent impact of that moon if the spacecraft were left in orbit.

10. Summary

The Galileo mission continues to persevere and provide world-class science. Each phase of the mission brings new and unique challenges along with discoveries that change the fundamental understanding of our solar system. The emphasis this past year, on understanding the solar wind and jovian magnetosphere interaction through cooperative measurements by Galileo and Cassini, is one of the highlights of outer planet exploration. A second campaign to observe Io is yielding new insights into volcanic processes on other bodies in the solar system. In addition to the scientific observations, Galileo's long-term operation in the harsh radiation environment around Jupiter sets benchmarks for future projects. The ongoing Galileo mission is a legacy to the teams that designed, built, and fly this robust and extremely capable craft.

11. Acknowledgments

The success of the Galileo Project results from the individual efforts of a large number of people, all of who deserve acknowledgment for their contributions. The Galileo Millennium Mission team contributed their dedication, experience, expertise and creativity to acquire the best science possible within limited resources. Paul Fieseler deserves special recognition as it was his curiosity and initiative in pursuing the mystery of Delta Velorum that yielded that unexpected discovery.

A special thanks is owed to Tiffany Chiu for her expert job of editing, layout, assembly, and production of this paper on time, despite the limited time to do so. Also, thanks are due to Wade Mayo and Alicia Allbaugh for preparing figures.

The current team operating the Galileo spacecraft today would like to express their appreciation and admiration for the team members of the past. Their hard work gave the present team the ability to deliver the outstanding science described in this paper.

The research described in this paper was carried out at ~~by~~ the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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